LOWLAND TECHNOLOGY INTERNATIONAL Vol. 6, No. 1, 33-41, June 2004
International Association of Lowland Technology (IALT), ISSN 1344-9656

EARTH SEWING TECHNIQUE FOR THE PRESERVATION OF FUNASAKO HISTORICAL KILN SITES

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ABSTRACT: The Funasako historical kiln sites, which are located in the northern part of Kyushu Island in Japan, have been considered as public exhibition areas. This requires preservation of the kiln remains by reinforcement of the soil. Considering the complicated local topography, the reinforcement method that was proposed is a combination of chemical grouting and soil nailing, and is termed the Earth Sewing Technique (EST) in this paper. In order to prevent disturbance of the soil in the kiln remains, a drilling hole diameter for soil nailing of 7 mm with a tendon (bolt) that has a diameter of 3 mm was selected. Field full-scale pullout tests at a model kiln site were carried out before applying the reinforcement technique to the real historical kiln sites. This paper presents the field pullout results and the results of a series of laboratory pullout tests that were conducted to investigate the critical factors affecting the performance of the EST. Design parameters have been recommended based on rational interpretation of the field and laboratory pullout test results. The pullout strength-water content relationships were found to be very useful for understanding and evaluating the shear strength capacity of soil nailing in partially saturated cohesive soils.

Key words: Historical kiln sites, model test, chemical grouting, soil nailing, pullout load

INTRODUCTION

Funasako kiln sites, which are located at Funasako Machi, Northern Kyushu, Japan, include the Chausuyama, Higasi, Udo, and Dougaheri kiln sites (see Fig. 1). The excavation and investigation of the remains began in 1994. Preservation of some ruins (1800 m^2) was carried out in 1995. The kiln sites might have been built between the second half of the 6th Century and the first half of the 9th Century. A photo of the Dougaheri No.2 kiln site taken during excavation is shown in Fig. 2. Dougaheri No.2 is a typical kiln site, and was used for burning the tiles for Buzen Kokubunji (founded in the year 756 AD).

For public exhibition purposes, the authorities requested the integration of the exterior and interior of the kiln remains. Considering the complicated local topography, the reinforcement method was designed using the combined technology of chemical grouting and soil nailing. Compared with traditional soil nailing, which uses drill holes and reinforcements of quite large diameters, the new technique, termed the "Earth Sewing Technique" (EST) in this paper, uses bolt and drill holes of small diameter.

In the design of a soil nail system, the pullout resistance of the individual nails is of paramount importance. Jewell (1990) and Bridle (1990) maintain that the normal stress between the nail and soil at failure increases as the effective overburden pressure increases. However, Schlosser (1982) proposed that the normal stress can be assumed constant with depth. This assumption was later confirmed by Cartier and Gigan (1983) in their field pullout tests, the results of which showed constant ultimate pull out force of soil nails located even at different depths. More recent studies by Heymann & Rohde (1992) pointed out that the ultimate shear stress is independent of depth in residual andesite. Obviously, theoretical study on soil nailing seems to lag behind the construction practice, especially in the aspect of shear behavior between grouted soil nails and unsaturated cohesive soils.

The objectives of the present study were: 1) to verify the feasibility of using EST for strengthening of historic sites and 2) to investigate factors controlling the performance of EST and to recommend appropriate design parameters. For this purpose, field full-scale pullout tests at a model kiln site were carried out. Pullout test results from the field kiln site are presented along with the results from a series of laboratory pullout tests.

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Note: Discussion on this paper is open until December 2004

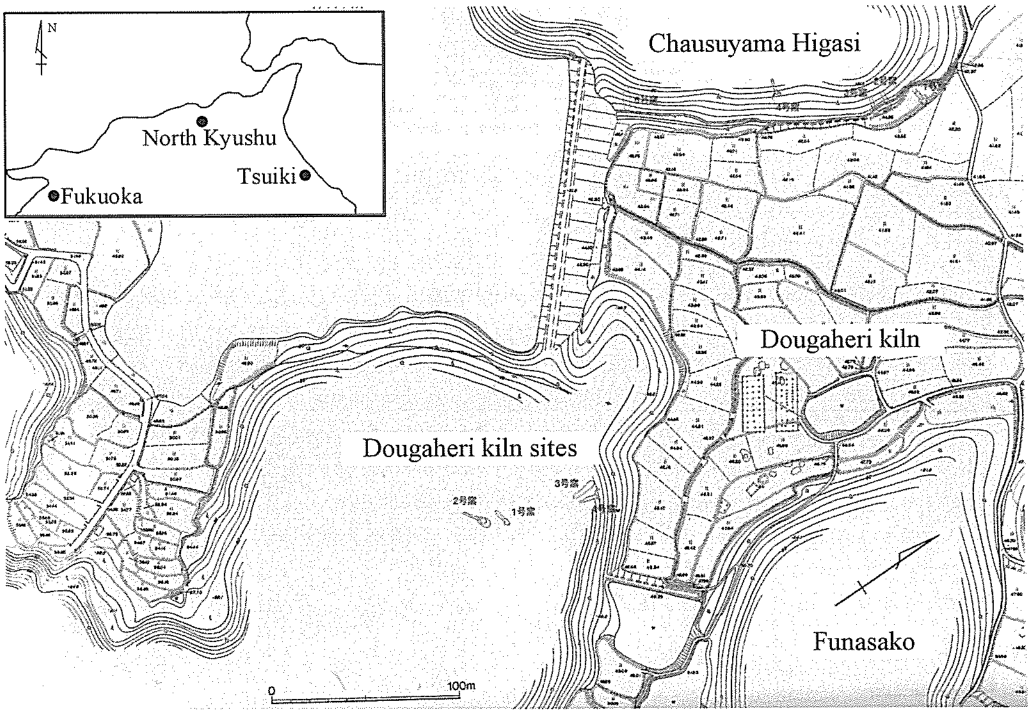

Fig. 1 Map showing location of Funasako kiln sites

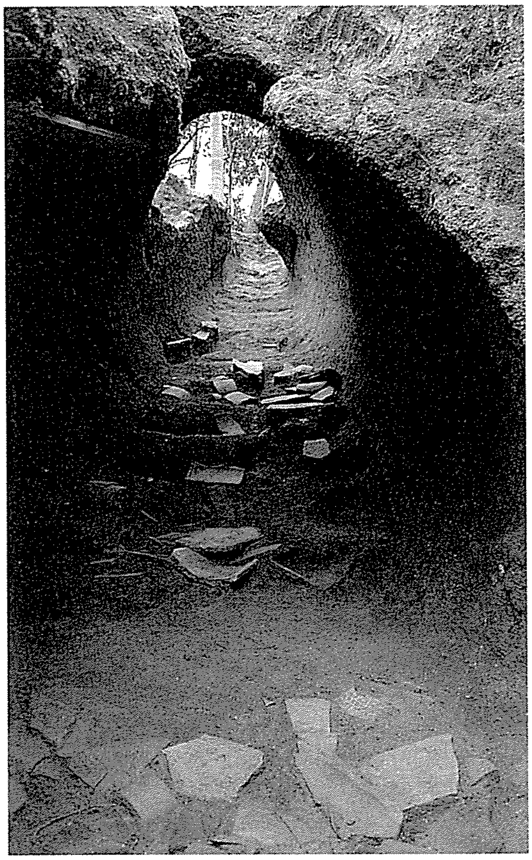

Fig. 2 Photo of Dougaheri No. 2 kiln site

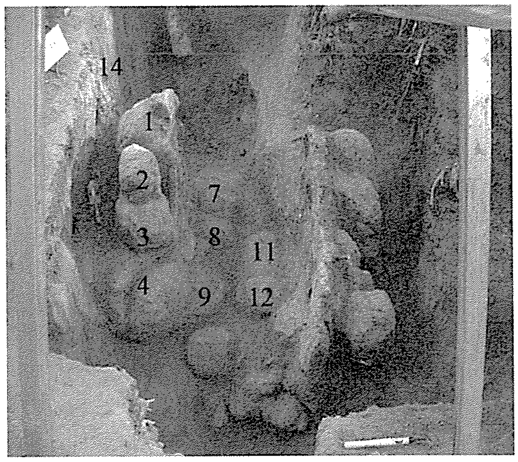

Fig. 3 Photo of field full-scale model kiln site

FIELD PULLOUT TESTING

General description

The field full-scale model test site is shown in Fig. 3, and is about 10 m away from the real site (Fig. 2). This site is very close to the historic kiln site and therefore would represent as well as possible the geotechnical conditions of the kiln site being investigated. The geotechnical properties of the soils at the site are listed in Table 1. The soil is

Table 1 Soil properties of Funasako kiln site

Property	Value
Specific Gravity, G_s	2.71
Grain size (%)	
Clay (<2μm)	34
Silt (2μm ~75μm)	12
Sand (0.075mm~4.75mm)	54
Plastic limit, w_p (%)	37.4
Liquid limit, w_L (%)	54.8
Field density (g/cm³)	1.21-1.31

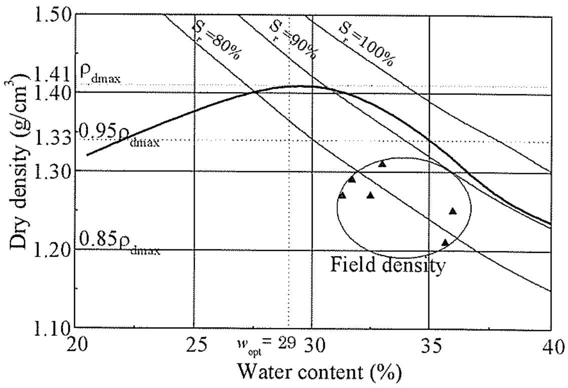

Fig. 4 Compaction curve of soil from Funasako kiln site

classified as sandy clay with some amount of silt. The standard laboratory compaction curve of the soil is shown in Fig. 4. The field density values are also plotted in Fig. 4. The density at the top layer of the test site was about 1.24 g/cm^3, and at the bottom was about 1.29 g/cm^3. The natural water content varied from 31% to 36%, with a degree of saturation of about 80%. The high degree of saturation might due to the rainfall that occurred a few days before extracting the samples.

The chemical grouting on the ground at the model site was carried out in 2001 using a self-developed drip-injection apparatus (Matsunaga et al., 2001). In 2002, the chemical grouted model kiln site was trench-excavated, and the solidified body was found to be of spherical shape with a diameter of about 300 mm. The EST was conducted in both chemical grouted soil (termed "With A") and natural soil (termed "Without A"). The drill hole diameter selected was 7 mm, the length 300 mm. The reinforcements were

Table 2 Summary of field pullout tests

Case No.	Test type	Soil type	Peak Disp. (mm)	Peak Force (kN)	Comment	Position
1	BNutExp 7%	With A	1.49	1.81	End	Upper
2	BNutExp 7%		2.69	1.66	End	
3	BNutExp 0%		1.31	2.63	End	Middle
4	BNutExp 0%		3.42	2.65	End	
7	BExp 7%	With A	3.38	3.00	Stop	Bottom
8	BNutExp 5%		3.06	3.00	Stop	
9	BNutExp 3%		4.38	3.00	Stop	
11	BExp 3%		2.41	3.00	Stop	
12	BExp 0%		3.67	2.29	End	
14-1	BNutExp 7%	Without A	15.04	0.45	End	Middle
14-2	BNutExp 5%		1.72	0.58	End	
14-3	BNutExp 3%		1.85	0.41	End	
14-4	BNutExp 1%		1.64	0.41	End	
14-5	BNutExp 0%		1.30	0.46	End	

Note:

Test type: B--Bolt (ϕ3mm), used as reinforcement (tendon); Nut--With inside and outside diameters of 3 mm and 6 mm, respectively, connected with bolt acting as small end anchor; Exp--Expan-K, expansion material added in cement grout.

Soil type: With A--the soil was solidified by chemical grout -Silicic acid ethyl; Without A--natural soil, which was not solidified by chemical grout-Silicic acid ethyl.

Comment: End--Pullout test was stopped when pullout displacement exceeded 20 mm; Stop--Pullout test was stopped when pullout force reached 3.0 kN, the maximum capacity of pullout equipment.

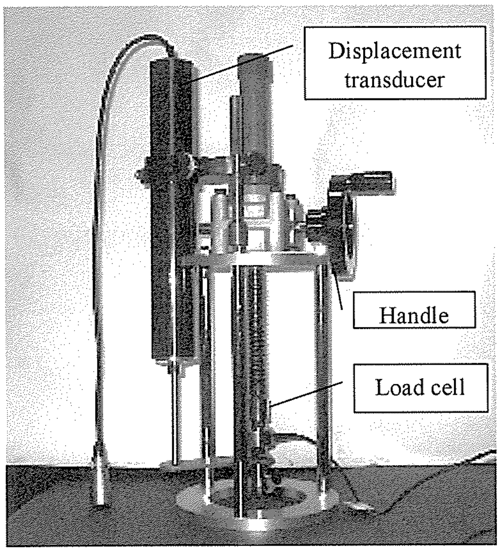

Fig. 5 Portable pullout equipment

threaded bolts with a diameter of 3 mm and a tensile capacity of 6.95 kN. Cement slurry (water/cement ratio = 0.45) added with expansion material (Expan-K) of different percentages (0%, 1%, 3%, 5%, and 7%, on a weight basis) was adopted as grouting material. A total of 14 tests (locations shown in Fig. 3) were conducted in both the chemical grouted soil and natural soil. The testing condition and a summary of the results are summarized in Table 2.

The pullout tests were performed after 3 months of reinforcement installation. The tests were performed using portable pullout equipment (Fig. 5). The pull out speed was controlled at 1.0 mm/min through the gear handle. Pullout displacements and pullout loads were recorded through displacement transducer and load cell, respectively.

Test results and discussions

Figure 6 shows the pullout force-displacement relationships for Cases 1, 2, 3, and 4, and Fig. 7 those for Cases 7, 8, 9, 11, and 12. All the 9 cases are nailed in chemical grouted soil (With A) with a water content of approximately 22%.

For cases 1 and 2, which were located at the upper portion of the trench, the bolt and cement grout were pulled out as a unit representing a rigid cylinder of about 8 mm in diameter, and no obvious crack was visually observed. The maximum pullout forces were 1.81 kN and 1.66 kN, respectively, which values were much lower than those for other cases. This may be due in part to the density at the upper portion being lower relative to that at other locations. For Cases 3 and 4, which were located at the middle layer portion, the maximum pullout forces were 2.63 kN and 2.65 kN, respectively. During pullout of the reinforcement, the solidified body of the chemical grout was found to have broken, and cracks were observed. The cracks could be the

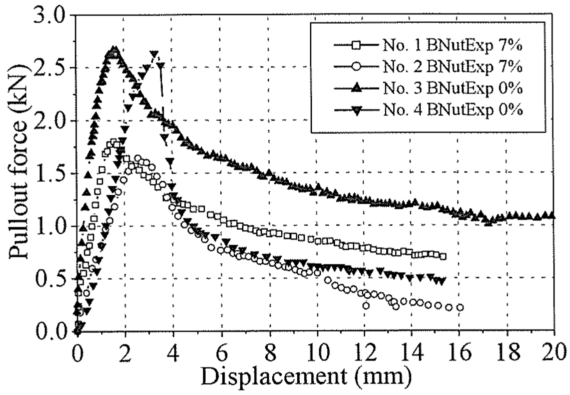

Fig. 6 Field pullout tests in chemical grout soil (With A, for Cases 1, 2, 3, and 4)

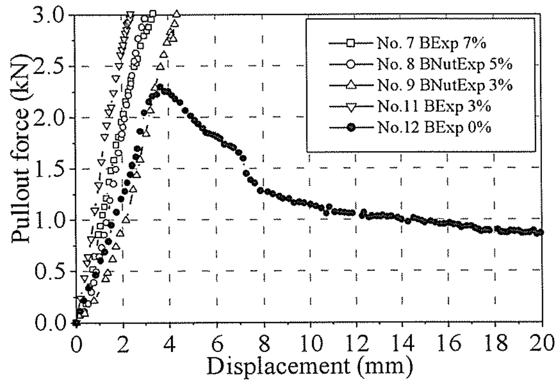

Fig. 7 Field pullout tests in chemical grout soil (With A for Cases 7, 8, 9, 11, and 12)

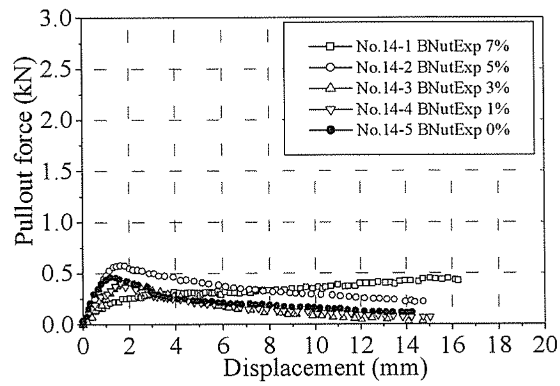

Fig. 8 Field pullout tests in natural soil (Without A, For Cases 14-1, -2, -3, -4, and -5)

reason why the ultimate maximum resistance was not fully mobilized in these two cases.

For Cases 7, 8, 9, 11, and 12, which were located at the bottom of the model kiln site, the pullout tests were stopped when the pullout force reached 3.00 kN (except in the case of No. 12) due to the loading limitation of the pullout equipment. No obvious cracks or breaking of the solidified body was observed. For Case 12, the maximum pullout force was 2.29 kN; the value is relatively lower in this particular location because of its poor chemical grouting.

Figure 8 shows the pullout results for Cases 14-1, -2, -3, -4, and –5, which were located in the natural soil nearby, where the chemical grout A was not used. The five cases, with different ratios of expansion material of cement slurry, gave an average pullout force of 0.46 kN, which was much lower than the results shown in Figs. 6 and 7. This may be due to the relatively high water content of 36% for test series of Cases 14, which represents the natural soil without chemical grout. These results are consistent with the laboratory test results presented in the next section.

LABORATORY PULLOUT TESTING

To investigate the controlling factors affecting the performance of EST, a total of 22 pullout tests were conducted in a laboratory setting. The general objective was to investigate the effects of the following parameters: 1) grouting condition on the failure mode; 2) ratio of Expan-K in cement slurry; 3) density and water content effect on pullout load. The details of this test series and its conditions are summarized in Table 3.

Table 3 Summary of laboratory pullout tests

Case No.	Test type	Soil type	Density (g/cm^3)	Initial water content (%)	Pullout water content (%)	Cement grout condition	Failure Mode	Comment
20	BExp 1%					Dry	I	
21	BNut Exp 1%	Without A	1.30	26	4	Dry	I	Failure mode study
22	BExp 1%					Wet	III	
30	BExp 0%							
31	BExp 1%							
32	BExp 3%	Without A	1.30	26	4	Wet	III	Ratio of Expan-K in cement slurry
33	BExp 5%							
34	BExp 7%							
40			1.30					
41	BExp 1%	With A	1.20					
42			1.10	26	4	Wet	III	Effect of density
50			1.30					
51	BExp 1%	Without A	1.20					
52			1.10					
60				26	4			
61				26	9			
62	BExp 1%	Without A	1.30	26	18	Wet	III	
63				26	24			Effect of water content
64				35	34			
70				26	9			
71	BExp 1%	With A	1.30	26	16	Wet	III	
72				26	25			

Note:

Testing type: B--Bolt (ϕ3mm); Nut--With inside and outside diameters of 3 mm and 6 mm, respectively, connected with bolt as small end anchor; Exp--Expan-K, expansion material added in cement slurry.

Soil type: With A-- the soil was solidified by chemical grout-Silicic acid ethyl; Without A--natural soil, which was not solidified by chemical grout-Silicic acid ethyl.

Initial water content: water content of soil while preparing the samples.

Pullout water content: water content of soil while pullout testing.

Cement grouting condition: Dry condition-- during cement grouting, water content of the soil was about 4%.
Wet condition--during cement grouting, water content of the soil was about 25%.

Failure Mode: Failure Mode I--failure at the tendon-grout interface; Failure Mode II--failure at the grout-borehole soil interface; Failure Mode III--failure within the soil.

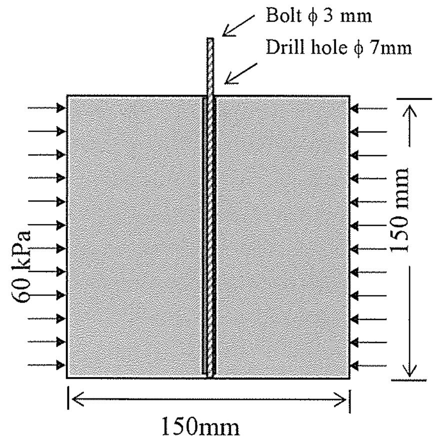

Fig. 9 Laboratory model test

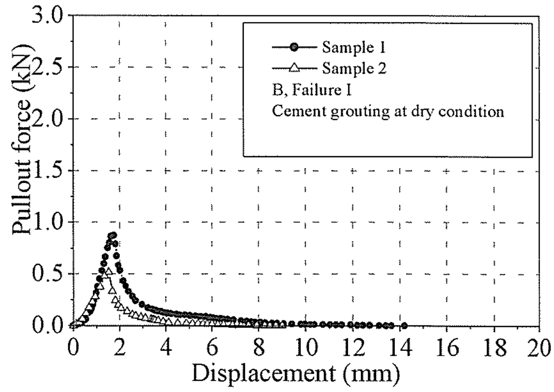

Fig. 10 Lab pullout test results for Case 20

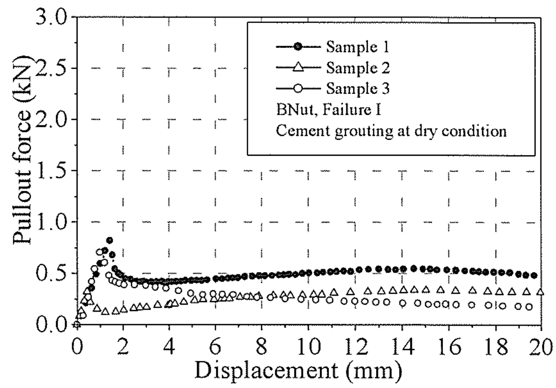

Fig. 11 Lab pullout test results for Case 21

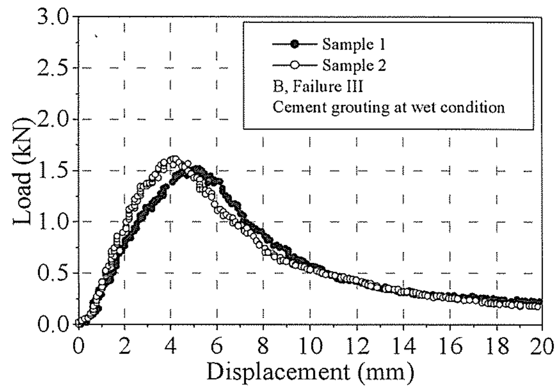

Fig. 12 Lab pullout test results for Case 22

The soils used for lab tests were sampled from the Funasako field model kiln site. The soil was compacted at a density of 1.30 g/cm^3 and had a water content of 26% in a PVC cylinder of diameter 150 mm and height 150 mm, as shown in Fig. 9. For specimens with chemical grouts, the grouts (injection ratio of 8%) were mixed with soil and then molded in a PVC cylinder by the compaction method. The density and water content were close to those of the field conditions.

Two alternate conditions considered for the drill hole and cement grouting were: a) Cement grouting at the dry condition; and b) Cement grouting at the wet condition. For cement grouting at the dry condition, the soil samples were prepared as described earlier and cured for 28 days. After curing, the water content of the soil was measured to be about 4%. At this condition, a hole was drilled and the cement grouting was done. The samples were cured for about 28 days and then pullout tests were performed. For cement grouting at the wet condition, the soil samples were prepared by the pre-described method and cured for 1 day in the curing room. The water content of the soil was measured to be about 25%. Then the drilling of the hole and the cement grouting were carried out. The samples were cured for about 28 days and then pullout tests were performed.

To prevent the breaking up of samples while pulling out, a confining pressure of about 60 kPa was applied at the lateral outside boundary of the specimen, as shown in Fig. 9. The pullout procedure and the equipment used are same as those used in field pullout testing.

Initial water content and failure mode

In pullout tests, the quality of cement grout will determine the failure mode. Generally there are three possible failure modes: 1) Failure at the tendon-grout interface (termed Failure Mode I); 2) Failure at the grout-borehole soil interface (Failure Mode II); and 3) Failure within the soil (Failure Mode III). Because, in the present EST, the thickness of cement grout was only about 2 mm surrounding the tendon (bolt), the quality of cement grout is more sensitive to the moisture of the surrounding soil. To investigate this sensitivity, cement grouting was conducted using the following two alternate methods: a) grouting at the dry condition; and b) grouting at the wet condition.

Figures 10 and 11 show pullout force-displacement relationships for Cases 20 (with a bolt used as a tendon) and 21 (a bolt with a nut used as a small end anchor (BNut)), respectively. Both cases represent the dry condition. Pullout failure mode was observed to be Mode I for both cases. The occurrence of this type of failure mode can be attributed to the following processes. Upon grouting, the water in the cement slurry might have been absorbed by the surrounding dry soil immediately, which would result in the lower strength of cement grouts. For both cases there is a sharp drop in pullout resistance after maximum pullout force, implying that the slipping might have occurred between the tendon and the grout interface. From the results shown in Figs. 10 and 11, it can be observed that the small end anchor (Nut) has little effect on the peak force. However, a higher residual force was observed in Case 21.

Figure 12 shows the pullout force-displacement relationship for Case 22. This is a typical case for cement grouting at the wet condition. Pullout Failure Mode II and Mode III were observed for all the specimens. The tendon and the cement grout were pulled out together as a rigid cylinder body with a diameter of about 7-9 mm. The pullout curve was relatively smooth.

Effect of the ratio of Expan-K in cement slurry

In order to increase the bond force between the cement grouts and the borehole side, the expansion material, Expan-K, was added at different percentages (0%, 1%, 3%, 5% and 7%, weight basis) to the cement slurry as grouting material. Figure 13 shows the unconfined compressive strength of the cement slurry with different ratios of Expan-K. It can be seen that the UC strength of cement slurry increases as the ratio of Expan-K increases from 0% to 3%. Beyond 3%, the increase makes little contribution. Cases 30, 31, 32, 33, and 34 were conducted with respective Expan-K ratios of 0%, 1%, 3%, 5%, and 7% in cement slurry to investigate its effect on pullout force. The maximum pullout force vs. Expan-K ratio relationships are shown in Fig. 14. The ratio of Expan-K in cement slurry seems to have little effect on the pullout force, which is consistent with the field pullout test results.

Effect of density

The density of the soil can vary under field conditions. This variation was investigated in the laboratory by conducting two series of tests (Cases 40, 41, & 42, and Cases 50, 51, & 52) corresponding to density variation of 1.10 g/cm^3, 1.20 g/cm^3, and 1.30 g/cm^3. Figure 15 shows the pullout force-displacement relationships for tests with chemical grout, Figure 16 the corresponding relationships for tests without chemical grout. The maximum pullout

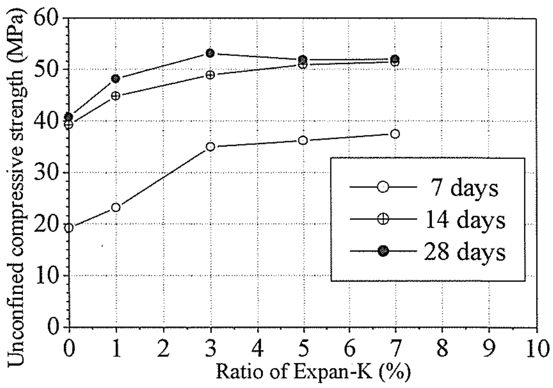

Fig. 13 Unconfined compressive strength vs. ratio of Expan-K in cement slurry

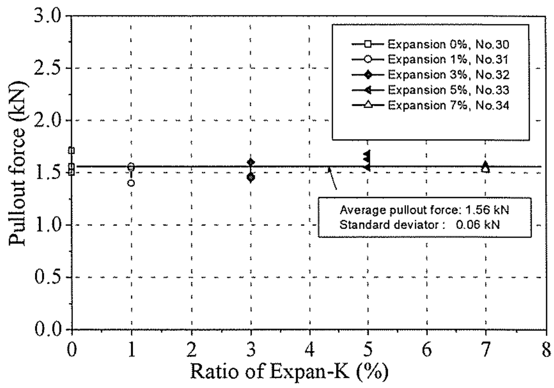

Fig. 14 Pullout force vs. ratio of Expan-K (Cases 30, 31, 32, 33, and 34)

force-density relationships for these two series are plotted in Fig. 17, showing significant effect of the soil density on the pullout force. At the same density, the first series has higher maximum pullout force than the second series. This implies that chemical grout A is effective at all densities. It should be noted the field full-scale pullout testing for Cases 1 and 2, which locations have relatively lower densities, showed lower pullout capacity, and thus confirmed the laboratory findings.

Effect of water content during pullout

The initial water content before grouting will affect the quality of grout, on which the failure mode would depend. Further, the pullout capacity depends on water content of the soil during pullout. In order to investigate this hypothesis, two series of samples were prepared with a density of 1.30 g/cm^3 and an initial water content of 26% (except in the case in which it was 33%) and grouted at the wet condition. Cases 60, 61, 62, 63, and 64 were on soil without chemical grout A, while Cases 70, 71, and 72 were with chemical grout A. The samples were cured at different seal-up conditions; so that the water content was varied within certain ranges while the pullout testing were

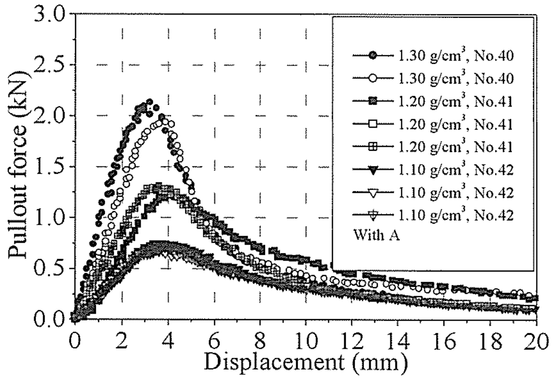

Fig. 15 Pullout force-displacement relationship of soil with A (Cases 40, 41, and 42)

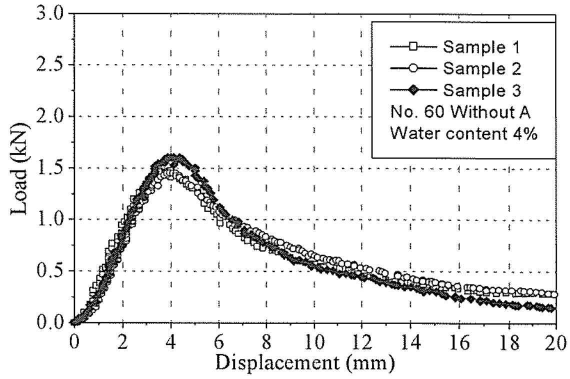

Fig. 18 Typical pullout results at low water content (Case 60)

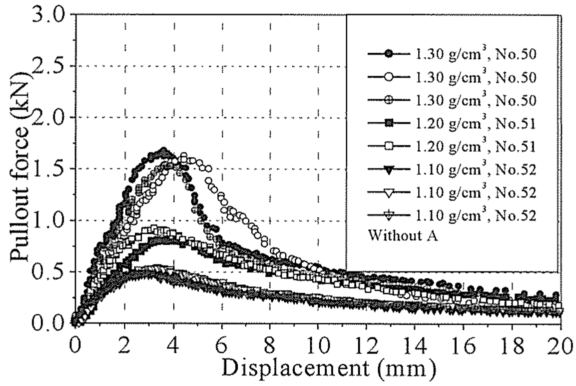

Fig. 16 Pullout force-displacement relationship of soil without A (Cases 50, 51, and 52)

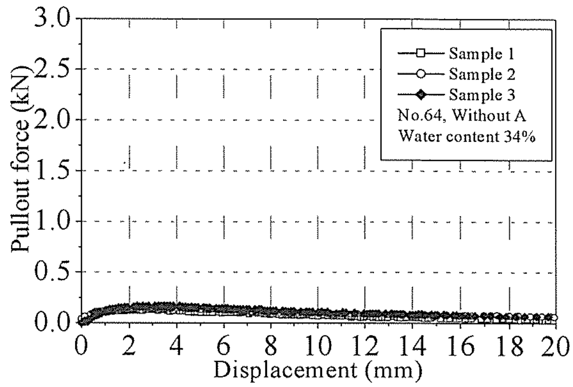

Fig. 19 Typical pullout results at high water content (Case 64)

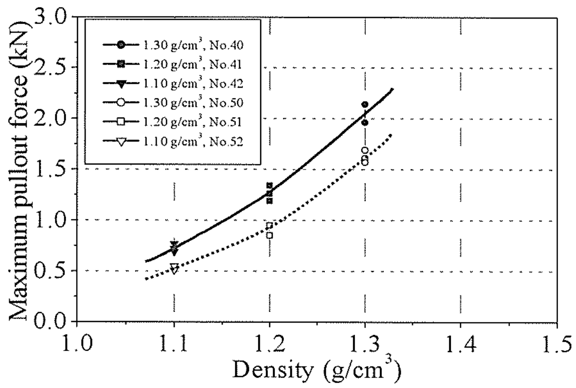

Fig. 17 Maximum pullout force-density relationship

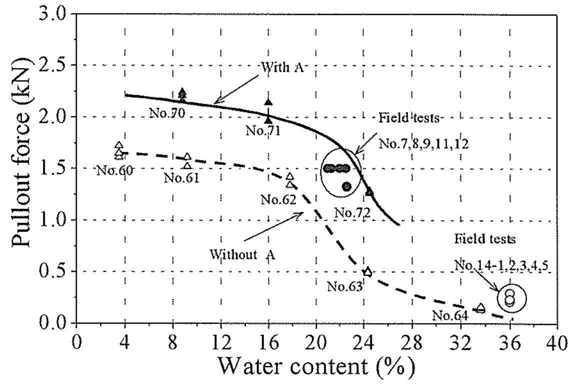

Fig. 20 Pullout force vs. water content relationship (Cases 60, 61, 62, 63, & 64 and Cases 70, 71, & 72)

conducted. The details of this particular testing series are summarized in Table 3.

Figures 18 and 19 show the pullout force-displacement relationships for Cases 60 and 64, which corresponded to the low (4%) and high (34%) water contents, respectively. The peak pullout forces are mobilized at a displacement of about 4 mm. This phenomenon is similar to the one observed in the field pullout tests.

The maximum pullout force-water content relationship for all the tests of the two series are shown in Fig. 20. It can be observed that there is an abrupt decrease of pullout capacity with the increase in water content to around 20-24%. The field pullout force corresponding to a length of 150 mm is also plotted in Fig. 20 (circular symbols). The field data matches well with the laboratory data. The pullout force-water content relationships developed in the

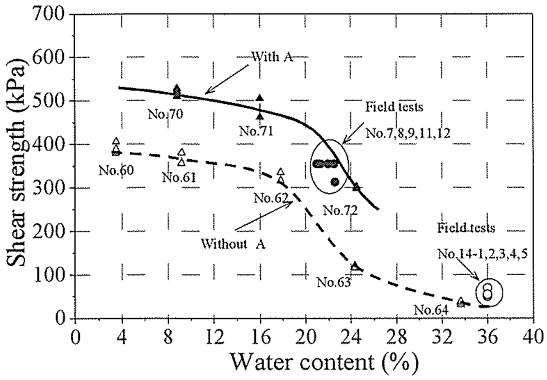

Fig. 21 Pullout shear resistance-water content relationship (Cases 60, 61, 62, 63, & 64 and Cases 70, 71, & 72)

laboratory can therefore be used for the determination of the design parameters. The ultimate interfacial shear strength between soil and reinforcement, as determined by pull out test, can be estimated as follows:

$$\tau_{ult} = \frac{P_{ult}}{\pi DL} \qquad (1)$$

where τ_{ult} = Ultimate interfacial pullout shear strength between soil and reinforcement; P_{ult} = Ultimate pull out force of soil nail; D = Diameter of nail or nail-grout combination; L = Nail length. In this study, for both field and laboratory pullout tests, the diameter of the nail-grout combination is observed to be about 7-9 mm. An average of 8 mm is used for the calculation of interfacial shear resistance in equation (1). From Fig. 20, the interfacial shear resistance-water content relationships have been computed and are presented in Fig. 21. These relationships indicate that the water content plays a significant role in the mobilization of the pull out shear resistance.

CONCLUDING REMARKS

In this study, from the objective of strengthening and preserving the Funasako historical kiln sites, a combined technology of chemical grouting and soil nailing, termed the Earth Sewing Technique (EST), has been investigated. The investigation was based on pullout tests. Pullout results in a field full-scale model kiln site and pullout test results in the laboratory settings are presented. The factors affecting the pullout load have been evaluated, and the following conclusions can be drawn:

1) EST is very sensitive to water content (in both the grout and the soil) before cement grouting. Failure Mode I (failure at the tendon-grout interface) occurred when cement grouting was performed at the dry condition; Failure Mode II (failure at the grout-borehole soil interface) and Failure Mode III (failure within the soil) were observed at the wet condition. In practice, it is important to ensure that the water content in the surrounding soil is more than 20% before cement grouting.

2) The small end anchor (Nut) has little effect on the peak force in Failure Modes II and III. However, a higher residual force was observed in Failure Mode I for tests with a Nut. In practice, the use of small end anchor is recommended.

3) In Failure Mode II (or III), the densities, boundary constrained conditions, and water contents are three critical factors affecting the pullout capacity. The pullout shear resistance-water content relationships determined in the laboratory setting can be useful in comparing and evaluating the shear resistance for soil nailing in residual cohesive soil.

4) The pullout force for cases with chemical grout was always higher than that for cases without chemical grout in all the tests.

5) The combined technology of chemical grouting and soil nailing is feasible for reinforcing and preserving the Funasako historical kiln site.

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